NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM

No. 1184

DEVELOPMENT AND CONSTRUCTION OF AN INTERFEROMETER FOR OPTICAL MEASUREMENTS OF DENSITY FIELDS

By Th. Zobel

TRANSLATION

"Entwicklung und Bau eines Interferenzgerätes zur optischen Messung von Dichtefeldern."
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DEVELOPMENT AND CONSTRUCTION OF AN INTERFEROMETER FOR OPTICAL MEASUREMENTS OF DENSITY FIELDS*

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Abstract: A method of interference is described in the present report which promises profitable application in aeronautical research. The physical foundation of the method and a simple method of adjustment are briefly discussed. The special technical construction of the instrument is described which guarantees its use also in the case of vibrations of the surrounding space and permits the investigation of unsteady phenomena. It is found that the interference method will make the small differences in density in the flow field around the body even at low speeds (40 m/sec) optically measurable.

Outline:

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*"Entwicklung und Bau eines Interferenzgerätes zur optischen Messung von Dichtefeldern." Zentrale für wissenschaftliches Berichtswesen bei der Deutschen Versuchsanstalt für Luftfahrt, E. V., Berlin-Adlershof, Forschungsbericht No. 1008, June 30, 1938.

1. INTRODUCTION

Optical methods of measurement have been more frequently used in modern measuring technique. This fact results from the progressive development of the separate technical fields of application as well as the continuous perfection of the optical instruments themselves and their control.

The interference methods range first among the optical methods of measurement which have become so important for highly accurate and exact quantitative measurements. Light is split into coherent wave trains which are brought to interference by means of simple but high-quality optical aids as mirrors and plane parallel glass plates. The interference fringes which were thus obtained are used for measuring small changes in density of the medium under investigation.

The present report describes an interferometer which was to be used mainly for investigation of the density field of bodies in the subcritical flow domain. This problem is especially difficult since, as is well-known, the changes of density in flows of low speeds up to about 100 meters per second are so small that the air may be treated as an approximately incompressible medium. There are no changes of temperature by heat-emitting bodies in air flows of this kind; therefore, only quantities are measured which are due to the small differences in density which result from differences of velocity in various places on the body.

Although the limit of measuring accuracy of the interference method is almost reached, this method still permits the optical measurement of these small changes in density. Therefore every means must be used in order to increase the measuring sensitivity.

Extreme accuracy of measurements and, equally important, most delicate adjustment of the interferometer are therefore required. A method of adjustment proved excellent in many tests of the author (compare reference 11) is briefly reported; by this method such an instrument can be adjusted with comparatively little loss of time. Then the precautions are described which were taken first to avoid deformations of the instrument by

temperature influences and second to reduce the sensitivity of the instrument against mechanical outside disturbances (vibrations) so that the method could be applied to technical measurements.

Finally there was the question of monochromatic light sources of high intensity to be solved; the relatively long light paths and the insertion of intermediate optical apparatus for the examination of unsteady phenomena made it difficult to reach sufficiently short times of exposure of about 1/100 to 1/200 second.

2. BASIC PHYSICAL STRUCTURE OF THE INTERFEROMETER

The following discussion is limited to straight parallel interference fringes. The formation of such interference fringes (as contrasted with interference rings) can be traced to the effect of a wedge-shaped plate (fig. 3). A second ray coming from L' shall be made coincident to the ray L reflected on the wedge-shaped plate at the point A; this second ray will leave the wedge-shaped plate, after refraction and reflection in it, at exactly the point A. The difference in path of these two reflected rays is a function of the thickness of the glass plate P at this particular location and of the angle of incidence α; the two rays come to interference in the image plane B_1 of the top surface of the wedge-shaped plate. At a constant angle of incidence "interference fringes of equal thickness" originate: light and dark straight fringes parallel to the edge of wedge. The effect of such plates depends on whether the incident ray of light is turned towards or away from the wedge. The separate rays of a light beam which are multiple-reflected in the wedge-shaped plate diverge or converge correspondingly.

This basic principle may be turned to advantage only after some changes have been made; it can be used for production of straight interference fringes in uniquely determined planes and for the examination of three-dimensional bodies by means of the four-plate system which is shown in figure 4. This optical arrangement was introduced by Mach and Zehnder; the two light paths are so far apart in space that a mutual

influence will be avoided if one of the two light paths crosses the field of density to be examined. This separation of the light paths is of decisive importance for the investigation of flow problems and thermodynamic phenomena.

Two of the parallel mirrors (fig. 4), S_1 and S_2, are coated for full reflection, the other two, P_1 and P_2, also called splitter plates, have a semi-transparent platinum coating applied by cathode sputtering.[1]

A light bundle incident on the plate P_1 is partially reflected, partially transmitted through the plate. The first bundle is transmitted through the plate P_2 after reflection at the mirror S_1; the second partial bundle is reflected at both the mirror S_2 and the plate P_2. These two light bundles are coherent, that is, they originate from the same light source and have the same polarization. They are used for interference after travelling light paths of equal length in the instrument. However, further partial reflections occur in the plates P_1 and P_2 which also cause phenomena of interference. But they are rendered so dim by the semi-transparent coating of the plates that a disturbing influence on the interference of the first partial bundle is avoided. With this arrangement the very complicated exclusion of the partial reflection is rendered superfluous which is necessary when using plane-parallel glass plates for P_1 and P_2.

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[1]A silvered mirror did not stand the test so well since the surfaces must not be varnished and since the silver layers decompose rapidly under atmospheric influences; moreover, they are mechanically very sensitive. The platinum surfaces, on the other hand, are chemically stable, but mechanically as sensitive as silver ones. A coating of silicon is recommended as giving the best reflecting effect; it is produced by Dr. Hochheim at IG-Farben according to a new method which was tested meanwhile.

By means of this instrument, interferences can be produced at any distance from the mirrors. (See fig. 5.) The phenomenon of interference always appears at the intersection of coherent light rays which have travelled different but equally large paths in the instrument. The two plates P_1 and P_2 alone permit any manipulation for production of interferences if the instrument is adjusted accurately, that is, if all mirrors are exactly parallel; moreover, the sum of the distances from P_1 to P_2 has to be so exactly alike on both different paths over S_1 and S_2 that the phase shift of the two wave trains equals zero.

All plates and mirrors are arranged in such a way that they can be turned around a pair of axes perpendicular to each other. The plate P_2 can also be shifted in the direction perpendicular to the plane of the plate on a sliding guide; thus the correction of the distance adjustment, still necessary after the "fine adjustment" of the instrument, is made possible. After the instrument has been perfectly adjusted the two full mirrors S_1 and S_2 remain unchanged for all further work. If possible, they ought to be fixed permanently.

The connection between the rotation of the plates P_1 and P_2, the location of interference and the width of the interference fringes can be defined as follows:

If the plate P_1 is turned by the angle α, the path of the first partial ray over S_1 and P_2 changes and the original intersection B on the screen shifts by an amount of $c = 2\alpha\,(a_1 + a_2 + l)$ to B'. (For these small angles, the sine of the angle may be assumed to be equivalent to the angle itself.) The second partial ray over S_2 and P_2 remains unchanged. The plate P_2 must be rotated in the opposite sense in order to obtain the interferences in B'. It is rotated by the angle

$$\beta = -\alpha\,\frac{a_1 + a_2 + l}{l}$$

The width of the interference fringes is then defined by the angle $\gamma = 2\alpha\left(\frac{a_1 + a_2}{l}\right)$ between the rays; the distance between two interference fringes will be

$$b = \frac{\lambda}{\gamma} = \frac{\lambda l}{2\alpha(a + b)}$$

therein λ represents the wave length of the light that was used; l the distance of the interference plane from the last plate P_2; a_1 and a_2 the distances between the mirrors and α the rotation of the first plate P_1. (Compare reference 7.)

The principle of the wedge-shaped glass plate for production of straight interference fringes that was shown in figure 3 is extended: the wedge angle is formed by misalinement of the two plane parallel plates which make rays of light of the same energy interfere and produce on the whole surface of the mirror interference fringes which lie on a uniquely determined plane. Therefore, interferences in any desired plane, position, and width may be produced by means of the two plates P_1 and P_2 and the four possibilities of adjusting them. Changes in sensitivity may be made by selection of an adequate width of the interference fringes. Herein lies the excellent adaptability of the interference method to the demands of all kinds of measuring techniques. If an approximately point light source is being used, rotations of the two plates about axes perpendicular to the plane of the paper (fig. 5) will cause interference fringes parallel to these axes; horizontal interference fringes will result from rotation about horizontal axes. All intermediate values between perpendicular and horizontal position of the interference fringes require coordination of the two plates and rotations around all four axes. The interference fringes always are parallel to the edge of the wedge.

3. METHOD OF ADJUSTMENT BY MEANS OF A PENTAPRISM

The preceeding statements on the basic working of the interference-refractometer made it clear that the accuracy depends on the order of magnitude of the light wave length. Therefore, the four plates and mirrors must be adjusted with the utmost caution; a special method of mirror adjustment is required.

In many cases where the interference method could contribute to the clarification of important questions its application was frustrated by the difficulties of adjustment of the instrument itself.

The principle of the adjustment method given in reference 5 shall be mentioned briefly; it requires certain conditions which can be fulfilled only in a laboratory-like setup of the mirrors on optical benches. Each mirror and its plate are fixed on an optical bench and arranged rotating about pairs of perpendicular axes; they are set parallel by observation of a point in the far distance (several kilometers) (fig. 6). The two reflected images of plate and mirror are made exactly congruent by means of a telescope which is also fastened to the optical bench and made parallel to it. The second pair of mirrors are set parallel in the same way. Since the image of the distant object reaches both mirrors, the error of the angular deviation φ increases with the distance of the mirrors and requires a correction by sighting at a celestial object, for instance a bright star. After these two pairs of mirrors have been set parallel, both optical benches are set parallel to each other and by means of adjusting screws on the sockets fixed in such a manner that illuminated cross-hairs in front of the plate P_1 become coincident for the whole system of mirrors. The disadvantages of this method of adjustment need not be discussed further.

A new method of adjustment was urgently needed which would make it possible to adjust the interferometer at the assigned location quickly, precisely, and without too much difficulty. Such a method of adjustment by means of a pentaprism was tested in many experiments and proved to be efficient. (See references 11 and 12.)

The pentaprism has the property of reflecting incident rays of light at 90°. (See fig. 7.) It is therefore not sensitive to angle changes in its whole field. Figure 8 shows the principle of the adjustment. First, the ground plane of the whole instrument on which all four mirrors are located will be set horizontally and the mirrors at 45° to the common line of their perpendicular axes of rotation. Then an autocollimating telescope F is adjusted exactly horizontal. Its optical axis is parallel to the mirror surfaces. In the direction of this optical axis there is an optical bench on which an adjustable stand with the pentaprism can be moved. The cross-hairs in the ocular of the telescope are then projected into the pentaprism and through the latter into the mirror. The mirror is rotated and inclined until the image of the cross-hairs which is reflected from its front surface falls back in the optical axis of the telescope and becomes fully congruent to the original cross-hairs.

Attention must be paid to a preliminary adjustment of the pentaprism itself, or else interferences will not be found. The pentaprism is not constructed with the exact accuracy that is needed here. Therefore the two images of the cross-hairs reflected by the anterior and posterior surfaces of the pentaprism are not exactly congruent. One therefore selects one of these two partial images for use and retains it for the adjustment of all mirrors. The base of the pentaprism is adjusted horizontally in both directions of the ray by means of a water level. The respective mirror is accurately adjusted when the two cross-hairs reflected from pentaprism and the mirror itself cover the one in the telescope.

Then the pentaprism is shifted on the optical bench and used in the same way for the adjustment of three mirrors. After that, the fourth mirror may be easily adjusted by eye by observing from P_2 an illuminated cross-hair in front of the first plate P_1 and making it congruent to the other reflected images. This observation ought to be made by telescope because the adjustment is facilitated and because it is easier to focus to a certain plane by telescope than by eye; this accomodation is important for the later focusing of the interferences.

If the mirrors were put parallel precisely, interferences must now be visible after insertion of a monochromatic light source in front of the plate P_1; these interferences are extremely fine because the interference plane is at infinity if the mirrors are absolutely parallel. In monochromatic light, the interference fringes are present also when the two different light paths in the instrument are not of exactly equal size but differ by a multiple of the wave length of the light that was used.

However, the criterion of perfect adjustment of the instrument is met only when the two light paths also are exactly equal. This adjustment of the accurate distance of the mirrors can be made on the slide mechanism (mechanism for longitudinal motion) of the plate P_2 by finding the so-called zero-interference in ordinary white light. The zero-interference is the phenomenon of interference which is characterized by a markedly distinct interference fringe in which all fringes of all colors that correspond to the zero-difference in the light paths coincide. The fringes to both sides of the zero-interference lose their well-focussed clearness by superposition of various wave lengths and disappear completely after a few fringe widths. (Compare figure 9.) The presence of this zero-interference in white light is also a criterion of the most delicate adjustment of the instrument in monochromatic light where it is no longer recognizable.

It is recommended always to start from this basic adjustment, for in the application to somewhat complicated fields of density the zero-interference must sometimes be used for identification of individual light fringes.

In the present case where the interferometer was set up for use in perpendicular arrangement the adjustment was made in horizontal position according to the method described above. Afterwards the instrument was rotated by 90° and used according to figures 1 and 2.

If, after adjustment of the instrument, interferences are present, the focusing of the interference fringes is made to the mean plane of the object under investigation. (See fig. 10.) A distinct object is placed at this location; the telescope is focussed sharply on that object,

and then the location of the interference is changed by means of the two plates P_1 and P_2 until it coincides with the location of the object and both are presented very distinctly at the same time. This image of the field of interference fringes is virtual. The location of the interference phenomenon lies really outside of the instrument, namely at the intersection of the two coherent ray bundles. The telescope may be replaced by a camera and an interference photograph may be taken. (See figs. 12 to 15.)

4. MONOCHROMATIC LIGHT OF HIGH INTENSITY

So far a light source as nearly pointlike as possible which emits only one single wave length λ was tacitly assumed in speaking of fields of interference fringes. But such a light source of absolute monochromasy does unfortunately not actually exist; rather, the radiation of a light source will always contain a great number of oscillations. As is well-known the spectral domain of the glowing filament of an incandescent lamp includes all wave lengths from the ultraviolet over the visible radiation to the heat radiation of the infrared.

On the other hand, luminous vapors or gases emit a spectrum with only a narrow extent and are therefore used as more or less homogeneous light sources for the purposes of interference. However, a further narrowing of the extent of the spectrum is usually necessary for the evaluation of photographs of interference fringes; color filters are used for absorption of the wave lengths which still represent a disturbance. However, such considerable losses of light result from these arrangements that short-exposure photographs of interference fringes and, therefore, the investigation of unsteady phenomena are no longer possible.

The present treatise also investigated the question what light sources are suitable to produce high light intensities and yet to meet the necessary stipulations of spectral properties.

The spectral domain presented by the sodium spectral lamp with the lines D_1 and D_2 $\lambda = 5890$ and 5896 AU is so narrow that one may speak of a monochromatic light source. This spectral lamp is especially suitable for interference purposes and for locating the interference fringes after the adjustment of the instrument because the whole image plane is always covered with saturated interference fringes. The light intensity of this lamp, however, amounts to about 25 to 30 sb only; it is so small that photographs with short exposure cannot be taken even when using panchromatic emulsions.

Osram's mercury spectral lamp is a light source of much higher intensity (about 1000 sb); moreover, it emits spectral lines of great fineness. The lines $\lambda = 4080$, 4360, 5460, 5770, and 5790 AU (fig. 11) represent the wave lengths which are emitted with relatively high spectral energy in the visible and photographically effective region. Since each light wave is able to produce a system of interference fringes the various systems are superimposed; the difference in paths of the separate light waves causes the disappearance of single fringes in certain places of the interference fringe photograph. Therefore an image of interference fringes results which consists of several periodically recurring groups of interference fringes (fig. 12) which cannot be used for spectral investigations. Therefore the monochromatism must, by suitable light filters, be intensified to the emission of a range of wave lengths as narrow as possible. Various light filters of the firms Schott and General Jena and Carl Zeiss were tested; the filter which gave the best photographic effect at the highest degree of monochromatic light was selected.

The loss of light by filtering is exceedingly high. Moreover, most filters have the property of well absorbing light waves up to about 5000 AU but with increasing wave lengths the transparency increases and becomes 100 percent in the domain of infrared radiation.

The blue line $\lambda = 4360$ as such is photographically very effective; but it renders the observation by eye so difficult that its use is eliminated.

For the green line $\lambda = 5460$ AU the panchromatic emulsion is not sensitive enough to obtain sufficiently short times of exposure even for the filter Zeiss B which permits to pass 67 percent of the relative spectral energy.

For the yellow line $\lambda = 5770$ and 5790 the use of the filter OG 2 (Schott and Gen.) proved to be most advantageous. It transmits 94 percent of the relative spectral energy of these lines which with 80 percent of relative energy stand out as the brightest lines in the visible domain of the line spectrum of the mercury lamp. (The energy of the spectral line is referred to the 100 percent energy of the ultraviolet line.).

This filter OG 2 is especially advantageous insofar as it absorbs completely the many wave lengths smaller than $\lambda = 5460$ AU which are contained in the spectrum of the mercury high-pressure discharge (Compare fig. 11.) Thereafter the transparency of the filter increases quickly. The transparency is only 14 percent for the line $\lambda = 5460$ AU, but for the desired lines with $\lambda = 5770$ and 5790 it is 94 percent; for all larger wave lengths, up to the domain of infrared radiation the filter will be perfectly transparent.

In the domain of visible radiation no larger wave lengths are emitted. The small infrared radiation is already absorbed by the glass elements of the lenses and mirrors. Thus practically the lines $\lambda = 5770$ and 5790 alone will be effective, with great energy, for the excitation of an interference fringe field with saturated interference fringes. The times of exposure which were obtained by insertion of a telescope were around 1/2 second for useful interference photographs. However, this long time of exposure is completely useless for the investigation of unsteady phenomena.

The next step towards an increase of brightness consists of the use of the mercury high pressure lamp type Hg B 500 which had been recently developed at Osram; this lamp produces a light intensity of 30,000 sb at a vapor pressure of 50 at. The line spectrum of the discharge in mercury vapor essentially varies with increasing vapor pressure and is indicated by an increased width of the lines until, at very high pressures of about 200 at, they run into one another as color bands.

The question had to be investigated whether the widening of the lines had reached disturbing proportions for $\lambda = 5770$ and 5790 in this lamp of highest light intensity. Fortunately, the result was that the widening of the bands only concerned the spectral lines of smaller wave lengths whereas the chosen lines $\lambda = 5770$ and 5790 retained almost constant width. The disturbing wave length domain may, therefore, be rendered ineffective and the high light intensity may be made useful for interference purposes by a filtration through the filter OG 2. For a saturated interference fringe photograph the attainable times of exposure with insertion of a telescope are 1/100 to 1/200. These values already offer the possibility of investigating unsteady phenomena.

5. INFLUENCE OF THE DEGREE OF MONOCHROMATIC LIGHT ON THE INTERFERENCE FRINGE PHOTOGRAPH

The ability of the light to produce an interference system depends upon two basic conditions:

(1) The two superimposed wave trains must oscillate with equal phase in one plane but do not otherwise influence one another.

(2) The light source must emit the same type of oscillation during the interval of time which is necessary for travelling the difference in paths of the two interfering ray bundles (coherency).

The ability of light to interfere is limited by the maximum path difference which still permits the observation of interferences. This path difference is a function of the width of the spectral lines and therefore of the uniqueness of the color (monochromasy).

If a light source emits as in the present case two adjacent homogeneous spectral lines of different wave lengths each wave by itself can produce an interference fringe system. The two fringe systems are superimposed and so nearly coincide if the difference in paths is small that apparently there exists only one fringe system.

One now increases the difference in paths and can make the observation that after the production of a certain number of interference fringes these fringes are progressively weakened and finally extinguished. They disappear completely when the maximum intensity of the system of one color coincides with the minimum of the other color. This phenomenon results from a change of the longitudinal motion of the plate P_2; the longitudinal motion causes the change of the difference in paths of the two interfering rays.

In the present case, the mercury high pressure lamp emits after filtration with the filter OG 2 the two adjacent wave lengths $\lambda = 5770$ and 5790 AU which differ by 20 AU. Therefore the fringe distance is different for the two colors, because the wave lengths are in proportion to the fringe distances:

$$\frac{\lambda_1}{\lambda_2} = \frac{b_1}{b_2};\; b_2 = b_1 \frac{\lambda_2}{\lambda_1}$$

Therefore the difference in the fringe distance of both fields of interference is:

$$b_1 - b_2 = b_1 \frac{\lambda_1 - \lambda_2}{\lambda_1} = 0.00346\ b_1$$

This difference is of such a small order of magnitude that it is negligible in the evaluation of the interference fringe photographs.

A shift in the position of the interference fringes after k fringes which can be calculated results from the emission of the two different wave lengths. The region where the fringes, counted from the zero-interference, just disappear is characteristic. This disappearance occurs when the difference in fringe distance in k fringes measures exactly one half of the fringe width: $\frac{b}{2} = kb\,\frac{\lambda_1 - \lambda_2}{\lambda_1}$ that is, the number of the fringes k beyond which this characteristic

place in the fringe photograph appears is independent of the fringe width that was adjusted:

$$k = \frac{\lambda_1}{2(\lambda_1 - \lambda_2)}$$

With $\lambda_1 = 5790$ AU and $\lambda_2 = 5770$ AU, k becomes 145, that is, counted from the zero-interference, the interferences disappear after 145 fringes or after every two k, $2k = 290$ fringes, respectively, a full saturation of interference fringes recurs periodically. A similar appearance of groups of interference fringes may be recognized in figures 12, 12(a), and 12(b).

If the light of a continuous light source, for instance an ordinary incandescent lamp is used, the limit of saturation for the interference fringes can be found by inserting for λ the mean wave length of the effective spectral domain of about 4000 to 6000 AU and for $\lambda_1 - \lambda_2$ one half of the difference of the two extreme wave lengths. $k = \frac{\lambda_1}{2(\lambda_1 - \lambda_2)} = \frac{5000}{2\times1000}$ $= 2.5$ fringes means that there exists only a total of about five saturated interference fringes in the whole field; figure 9 confirms this fact.

Reference 8 and reference 9 treat the evaluation of interference fringe photographs; the theoretical relations between the density which was optically determined and the other state variables pressure and temperature are derived there.

6. TECHNICAL POSSIBILITIES OF APPLICATION OF THE INTERFEROMETER

The extraordinary sensitivity of the interference method permits measurement of changes of index of refraction of matter of 1/20,000,000 (length of the measured region 1 m). The region of sensitivity

may be changed extensively by adequate selection of width of the fringes; the width can be adjusted in any way by means of the two plates P_1 and P_2. (See figs. 5 and 15.) For instance, for large changes in density very narrow fringes will be selected because a wide bulging of the fringes is to be expected; very small changes in density, on the other hand, call for greater widths of the fringes. For the extreme case, investigation by means of very wide fringes will be used for small fields of density.

To understand the extent of sensitivity of this measuring method one should bear in mind that in cases of wide interference fringes small fractions of this width can still be measured accurately, and yet a bulge of one whole fringe width corresponds to a change of the optical path of one light wave length only (0.578/1000 mm).

Thermodynamics, flow problems, gas dynamics, the determination of density in static gaseous and liquid matter, of transparent solid substances and stress analysis for transparent solid and liquid substances are the main fields of application of the interference method.

The application of the interference method is of special importance in the investigation of bodies in a flow at high velocities in the region of subsonic flows. At the high flight velocities already planned and under the influence of compressibility, local sound waves appear on the wing profile; these sound waves influence considerably the properties of drag and lift and therefore the flight characteristics of the body. The optical measuring method is especially valuable in this critical flow domain where methods of measurement that were proved good in wind-tunnel practice at lower air speeds are no longer applicable. Furthermore, the method of interference permits the investigation of unsteady flow phenomena on the wing as for example occur with the sudden extension of split flaps, or the extension of nose flaps, or the opening of slots, etc. The variation of the interference fringe field which is a measure for the variation of the field of density in the medium under investigation occurs free of inertia.

7. TECHNICAL PECULIARITIES OF THE INTERFEROMETER

The fact that by an optical system of plates and mirrors and a special precision adjustment of these aggregates to each other light may be brought to interference does not yet give any certainty as to whether such an instrument is appropriate for technical measurements. Mostly special conditions of set-up, which are not possible in technical application, had to be fulfilled for the interferometers of this kind known so far; by the way, only a very small number of them existed in Germany until a few years ago. They were set up horizontally on a very heavy and solid ground plane in rooms free of vibrations or on especially fabricated foundations and in rooms which had partly thermostatically regulated temperatures. Yet, circumstances permitting, the heat emanation of the human body when near the interferometer was sufficient to make the interferences disappear; in sensitive adjustment, small deformations of the instrument resulted from this influence of temperature. Sometimes a light pressure of a finger on that ground-plane weighing several zentners[2] was sufficient to change the interferences.

The conclusion had to be drawn from these observations that first of all the sensitivity against temperature and against mechanical influences must be eliminated by a more favorable technical setup. Therefore for the first time a lattice support was built which was cantilever and shaped according to the principles of bridge construction, but elastic in itself; this lattice carrier supported the mirror aggregates. (See figs. 1 and 2.)

To equalize the temperature a special invar-steel alloy was selected which is far superior to steel; its longitudinal expansion coefficient, when heated to 100° centrigrade is $\alpha = 0.000009$ as contrasted with the longitudinal expansion coefficient of steel $\alpha = 0.00165$. The lattice system must not be welded because these outstanding properties of the invar-steel are lost again by a change of structure as it occurs in welding.

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[2]A zentner = 110.23 pounds.

Furthermore, the instrument was constructed for perpendicular arrangement and suspended floating in a frame of tubes by means of springs so that it was freely movable in all three directions of space. The natural frequency of the instrument $\omega_e = \sqrt{\frac{c}{m}}$ can be adjusted to the circumstances by an adequate selection of the spring constant c if the mass m of the instrument is given. The selection of a natural frequency much smaller than the present stimulating frequency of the vibrations which have effect upon the instrument from the outside will prove practical. Then the vibrations are rendered innocuous and the damping is sufficient so that the interference fringes remain unchanged and measurements are possible even in rooms with large vibrations.

The mobile arrangement is a further peculiarity of the instrument; large fields of density may thus be measured in various locations by means of the small mirrors which are available.

The optical apparatus which is used for taking the interference photographs is most practically fastened to the interferometer itself on a small optical bench; it joins in every move of the instrument so that the full field of interferences is always illuminated irrespective of the position in the field of density to be investigated.

If the body under investigation is more extended in length (for instance, a heated pipe or the span in the model of a wing) an optical distortion results because the two boundary planes lie at different distances from the lens. This fact must be taken into consideration already when setting the camera with respect to the body under investigation; the body must be adjusted in such a manner that two fixed points at the corresponding locations of the boundary planes lie exactly in the optical axis.

This distortion can be minimized by first deflecting the light coming from the interferometer through prisms and thus extending the object distance. This method is advantageous for the reason that one can work with great

focal distances of an optical apparatus and that one can fasten the optical apparatus directly to the interferometer in spite of the great distances from the object under investigation. The small loss of light by absorption of the air on the path outside of the instrument which was lengthened artificially is unimportant; for the light at our disposal is approximately parallel and so bright that times of exposure down to 1/200 second are possible when a light filter is used.

Finally, I should like to mention that the use of thick glass plates as boundary planes of the density field to be investigated does not present any difficulties. Glass that is optically flawless and free of stress and regions of varying refractive index should be used; however, it need not be exactly plane parallel.

Only a correct compensation of the phase shift is important in the use of plates of this kind. If this phase shift is made by adjusting the interferometer with regard to distance (micrometer slide at P_2), a second adjustment of the mirrors might be necessary as the plates are not exactly plane parallel.

However, there exists a much simpler method: one can insert a glass plate into the second light path which was so far undisturbed; this glass plate should be approximately as thick as the two boundary plates of the density field put together. If this compensator plate can be revolved and inclined, interferences of good quality will be found again without a change in the exact basic adjustment of the instrument. As long as these glass plates are being used the interferences also can be changed in any way by the two mirrors P_1 and P_2.

8. SUMMARY

The physical foundations of an interference method were discussed; an interferometer was described which was developed for the optical measurement of density fields. The technical structure of the instrument itself was stressed; also an adjustment method which eliminated difficulties in the adjustment and control of such instruments that were hitherto considered very intricate.

The light sources which are most appropriate for spectral examinations and filtering which is adequate for a high degree of monochromatic light and photographic effectiveness were investigated; as a result photographs of saturated interference fringes (compare figs. 13 to 15) with times of exposure of 1/100 to 1/200 s were obtained even for long light paths in filtered light. The results of the present treatise make the application of interferometers to the most delicate measurements of density possible, even for industrial applications; they also render the investigation of unsteady problems feasible; therewith the way is paved for an introduction of the inteference method into many technical fields of application.

The observation of the region of interference on a wing model of about 10-centimeter chord and 40-centimeter span showed already at a flow velocity of 40 m/s characteristic bulgings of the interference fringes near the profile surface. The sensitivity of the measuring method increases linearily with the extension in length (span) of the region under investigation; the changes in density to be measured increase with the flow velocity. Already for a span of about 2 meters and velocities of 100 to 200 m/s there result bulgings of the interference fringes which can be calculated; their magnitude is such that very small fringe distances must be used. Herewith the assumptions for the determination of the density field which surrounds bodies in a flow and for the investigation of numerous important flow problems are given.

At the time these observations in the wind tunnel were made spectral light sources of highest intensity had not yet been analyzed; therefore these interference photographs could not yet be taken.

After the problem of illumination had been solved the wind tunnel was, by a technical mishap, shut down for several months; therefore such interference photographs about bodies in a flow will be published later.

Translated by Mary L. Mahler
National Advisory Committee
for Aeronautics

9. REFERENCES

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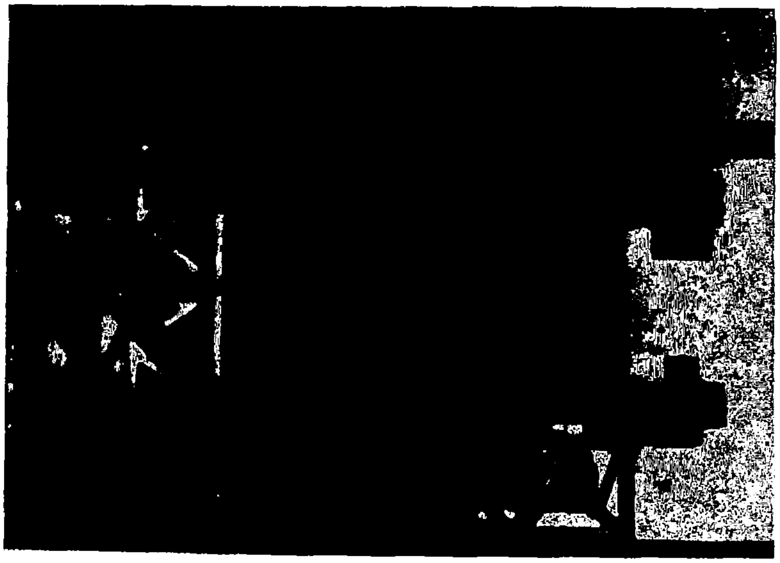

Figure 1.-

Figure 2.- Mobile and floatingly suspended interferometer.

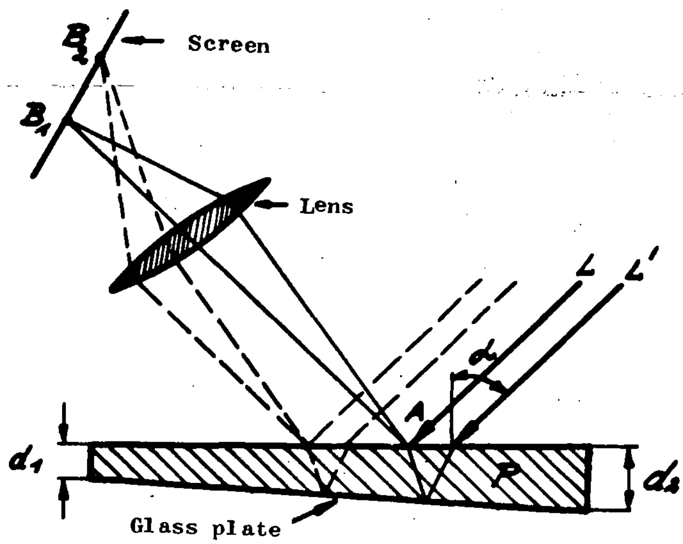

Figure 3.- Formation of interferences of equal thickness at the wedge-shaped plate (L 12).

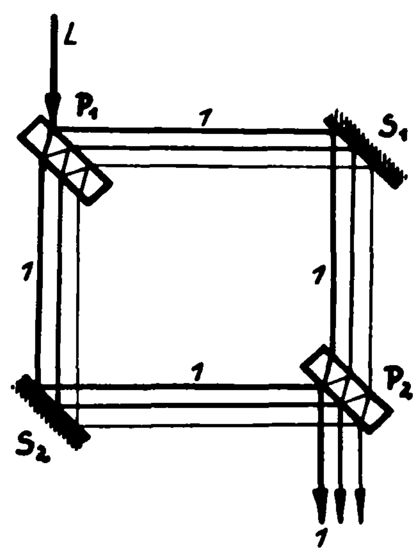

Figure 4.- Four - plates— system according to Mach and Zehnder (L 11).

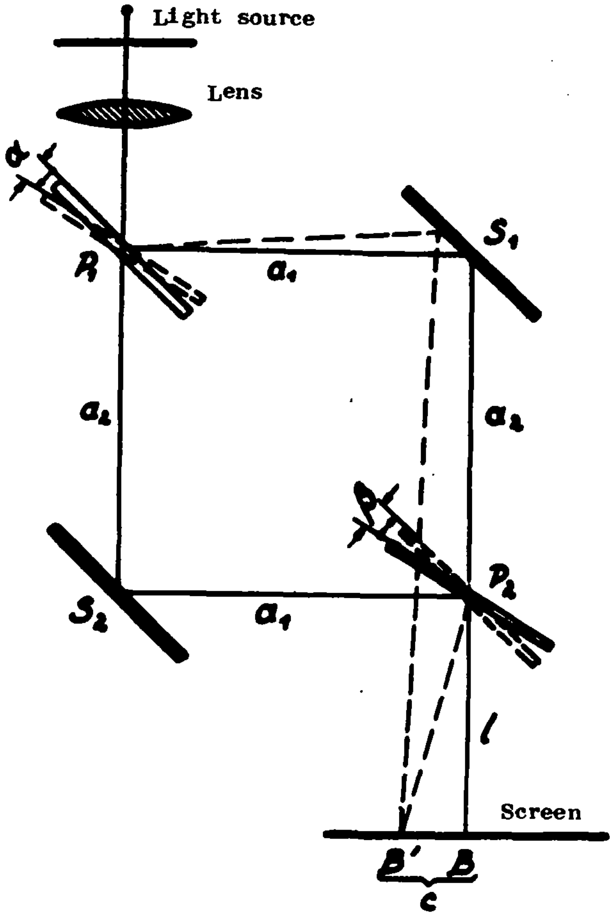

Figure 5.- Generation of the interference phenomenon at any distance from the instrument by mirror adjustment (L 12) (B' is the location of the interference phenomenon.)

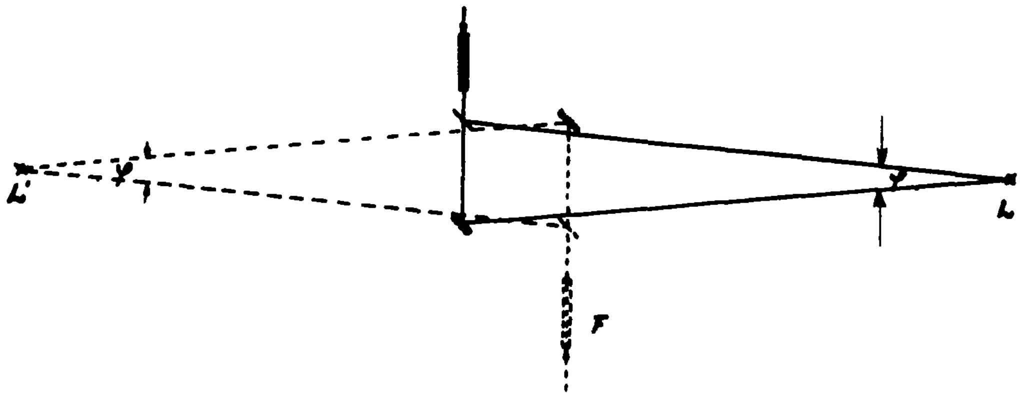

Figure 6.- Parallel adjustment of a pair of mirrors at a time by observation of a remote object.

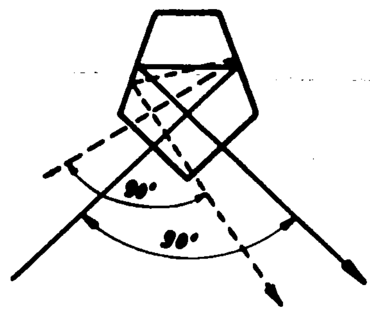

Figure 7.- Paths of the rays in a pentaprism.

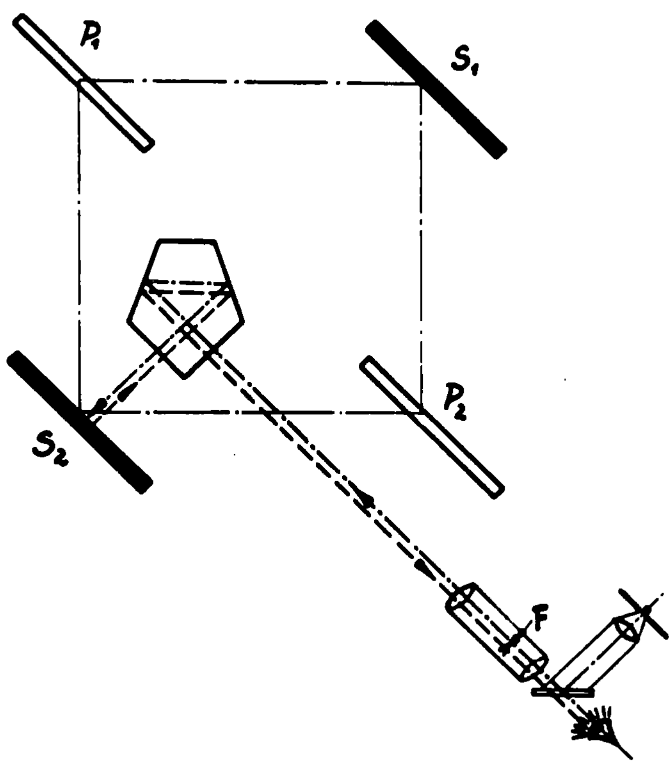

Figure 8.- Adjustment of the mirrors by means of a pentaprism (L 11, L 12).

Figure 9.- Zero - interference in continuous white light.

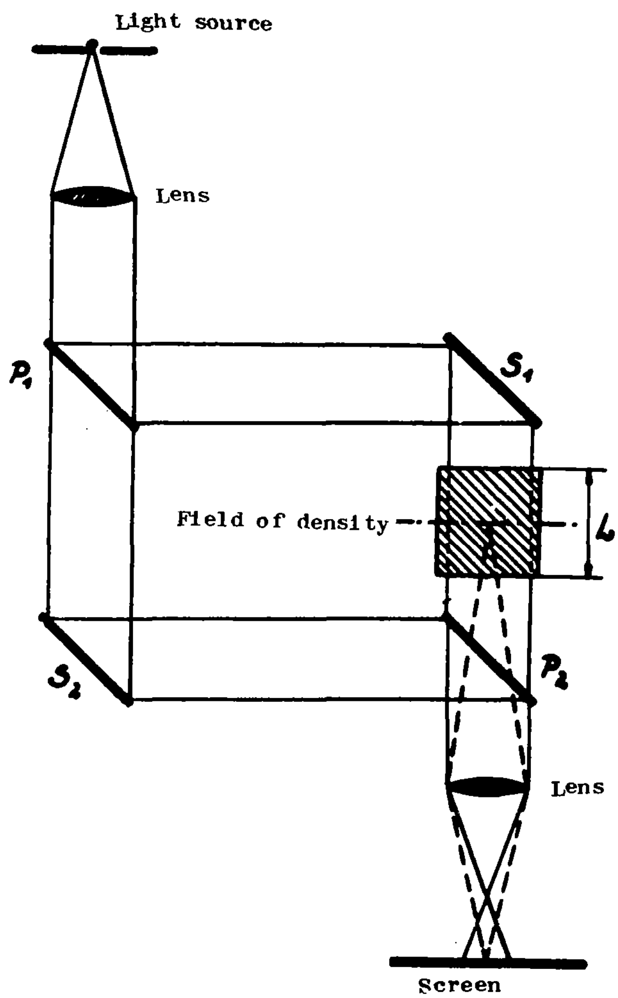

Figure 10.- Setup of the interferometer for taking the interference fringe photographs.

Figure 11.- Relative spectral energy distribution of the mercury high-pressure discharge (from Z. f. techn. Physik; 14; 1933, 393)

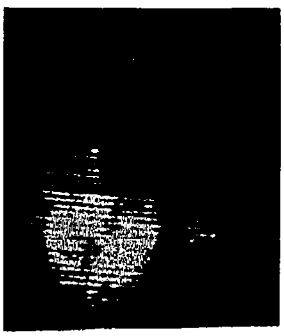

Figure 12a.- Without density field.

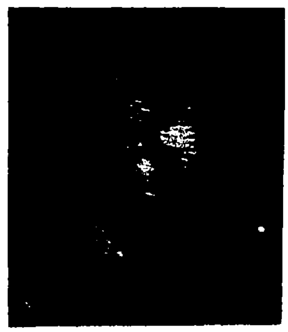

Figure 12b.- With density field.

Figure 12.- Groups of interference fringes in unfiltered mercury light. Time of exposure: t = 1/500 sec.

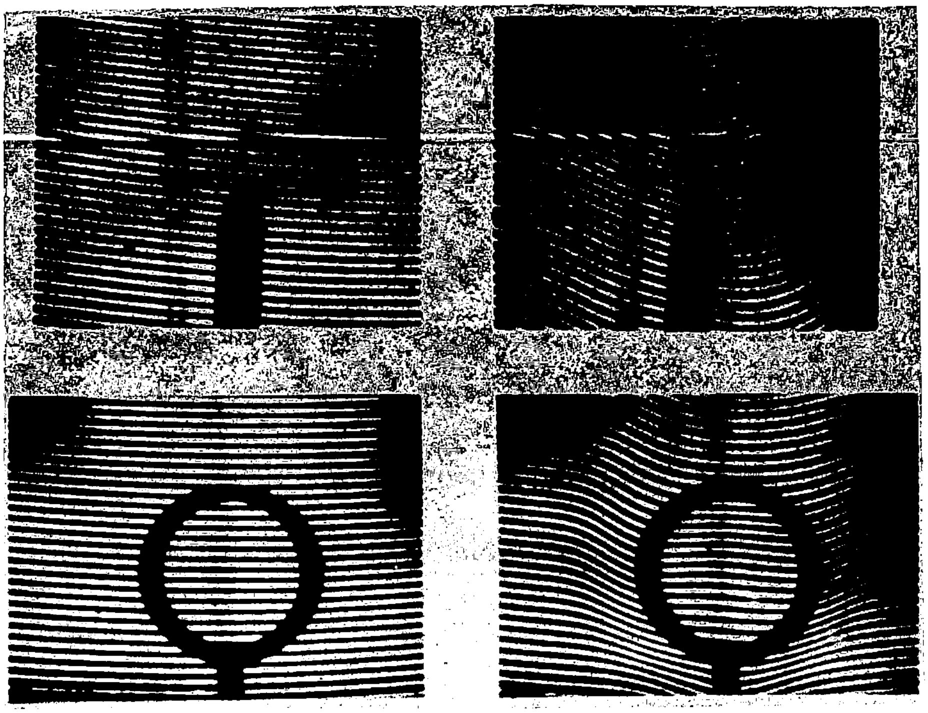

Figure 13.- Displacement of fringes in the proximity of a heated body. t = 1/100 sec.

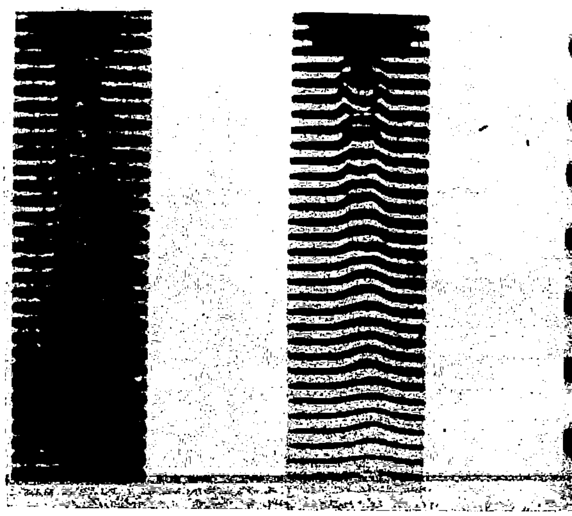

Figure 14.- Displacement of fringes by changes in density in supersonic flow (L 11). t = 1/100 sec.

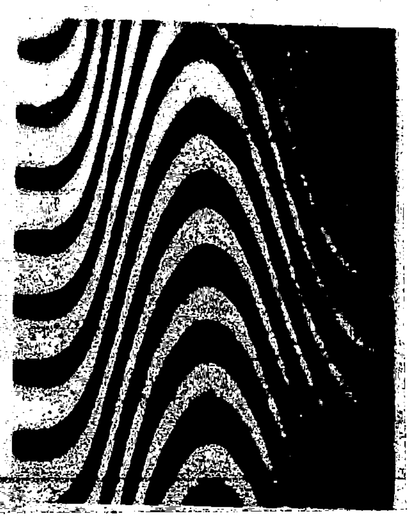

Figure 15.- High-degree deformation of the interference fringes by large changes in density of the medium under investigation. t = 1/100 sec.